NASA Trace Gas Products for Air Quality Applications

Atlanta

September 1 – 3, 2015

ARSET

Applied **R**emote **SE**nsing **T**raining

A project of NASA Applied Sciences

Satellite Remote Sensing of Trace Gases for Air Quality in a Nutshell

- **Surface Monitoring:** Satellite trace gas instrumentation is generally not sensitive to surface pollution compared to aerosol instrumentation, ***with the exception of nitrogen dioxide and sulfur dioxide***

- **Emissions Inventories and Modeling**: Trace gas observations from space have been useful for constraining emissions inventories

- **Vertical profile information in the free troposphere** is also available for some products (e.g. CO) and derived using the pressure dependence of spectral bands

Satellite Remote Sensing of Trace Gases for Air Quality in a Nutshell

Nitrogen Dioxide
Good sensitivity in the planetary boundary layer (PBL): fire smoke, industrial and transportation sources, stationary sources, top –down emissions inventories

Sulfur Dioxide, ozone and formaldehyde
Limited sensitivity in the PBL. Sulfur dioxide is sensitive to large point sources, such as electrical generating units and volcanoes

Carbon Monoxide
Good mid-tropospheric sensitivity, useful for monitoring long range transport of smoke.

Carbon Dioxide and Methane
Low spatial resolution but captures global trends

Measuring Trace Gas from Space

1. Satellites detect backscattered solar radiation and/or emitted thermal radiation

2. We know the distinct absorption spectra of each trace gases.

3. By knowing how and by what amount different molecules absorb radiation at different wavelengths, we can identify a "fingerprint" for each atmospheric constituent.

4. Based on the radiation measured by the instrument, retrieval algorithms (a model) are used to infer physical quantities such as number density, partial pressure, and column amount.
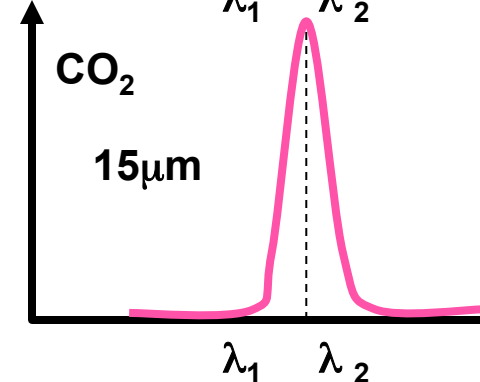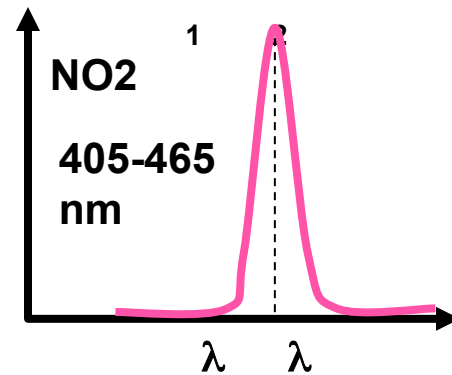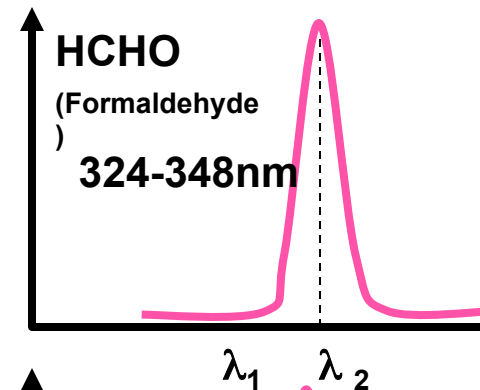
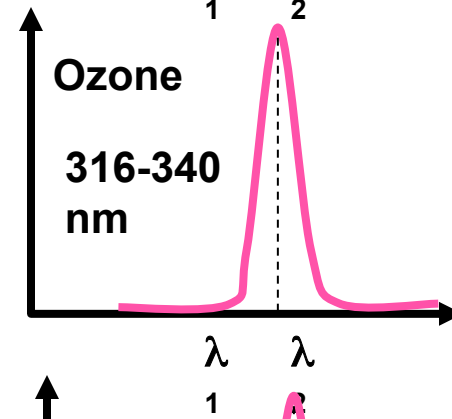**Scattered/emitted radiation detected by satellite**

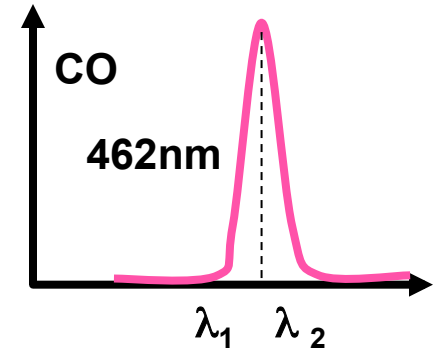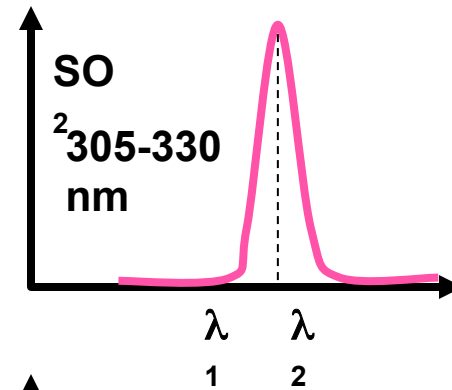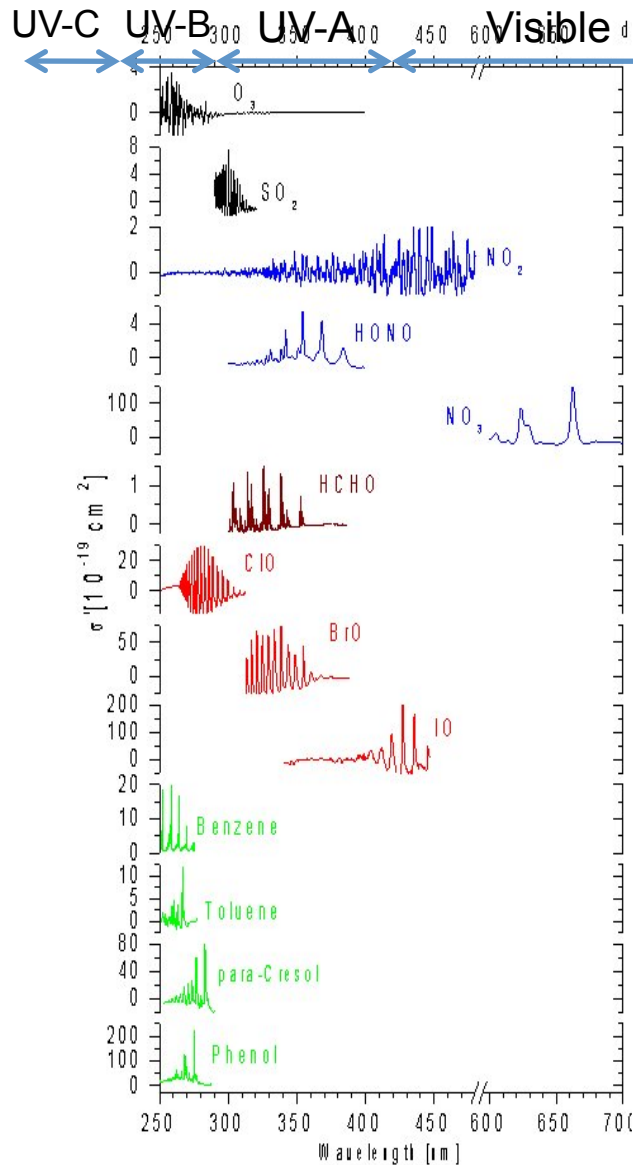**Trace Gas Absorption**
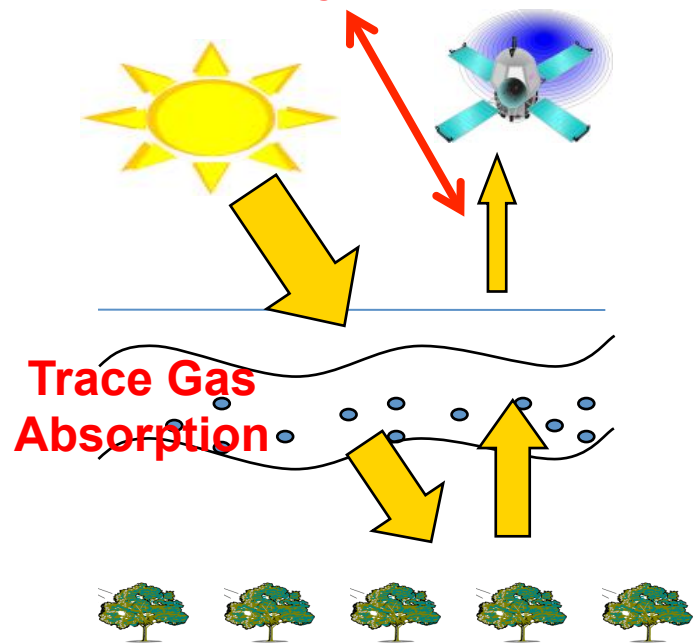
How Satellites Measure Trace Gases
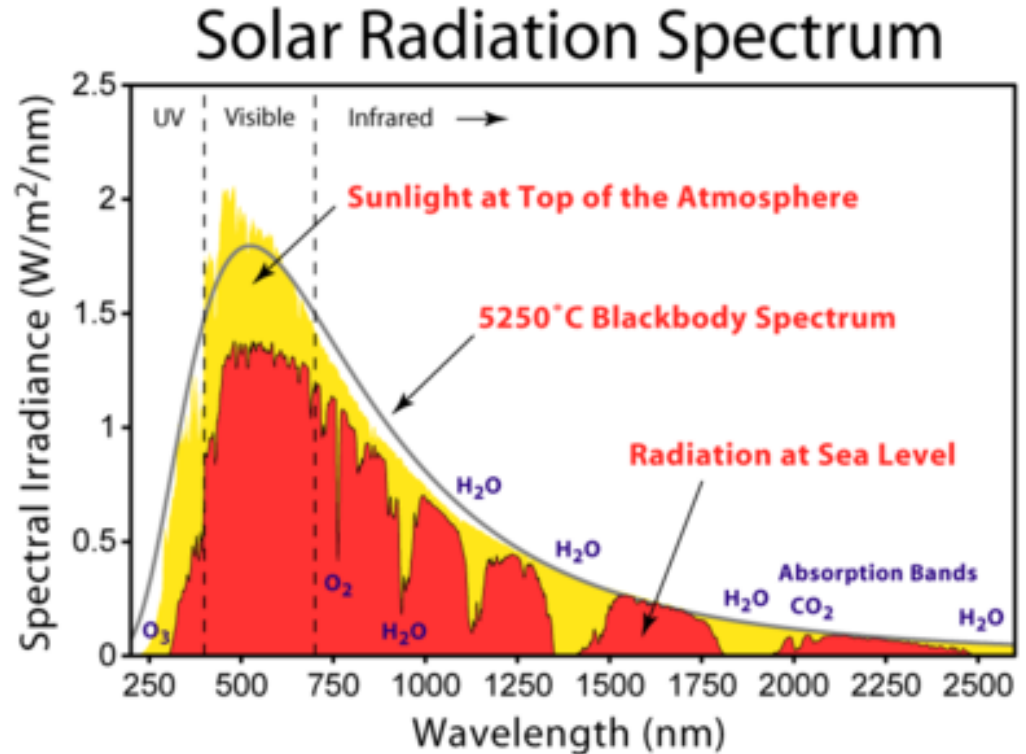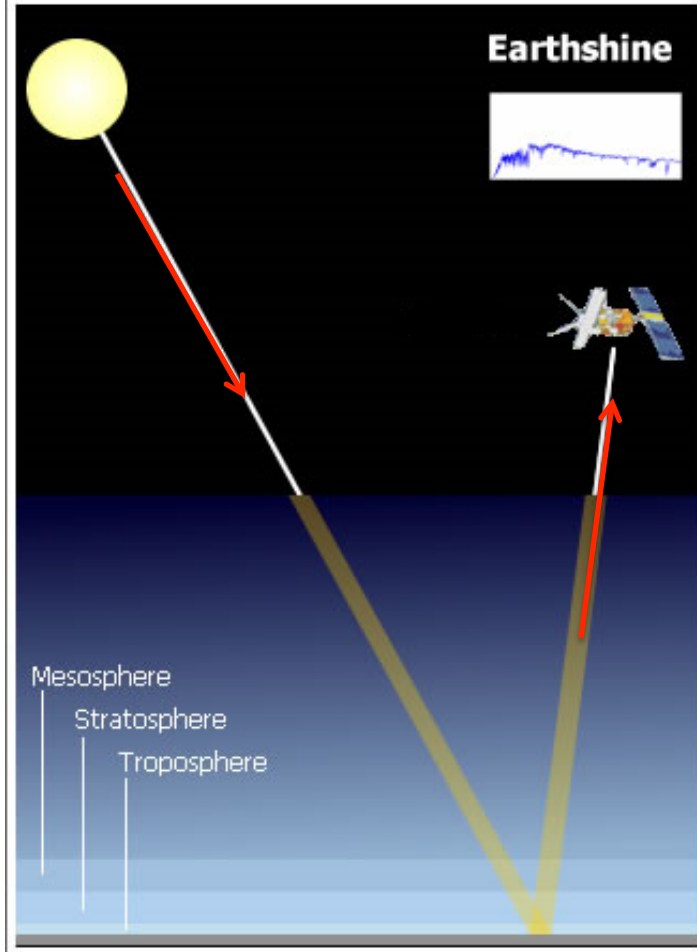
Unlike remote sensing of aerosols that use the signature of aerosol scattering, remote sensing of trace gases uses the signature of gas absorption.

All satellite remote sensing measurements of the troposphere are based on the use of electromagnetic radiation and its interaction with constituents in the atmosphere.

# Satellite measurements take advantage of distinct absorption spectra

UV-C   UV-B   UV-A   Visible

O_3

SO_2

NO_2

HONO

NO_3

HCHO

ClO

BrO

IO

Benzene

Toluene

para-Cresol

Phenol

$\sigma\,[10^{-19}\ cm^2]$

Wavelength [nm]

250   300   350   400   450   600   650   700

SO$_2$ 305-330 nm

λ_1 λ_2

CO 462nm

λ_1 λ_2

Ozone 316-340 nm

λ_1 λ_2

HCHO (Formaldehyde) 324-348nm

λ_1 λ_2

NO2 405-465 nm

λ_1 λ_2

CO$_2$ 15μm

λ_1 λ_2

Vertical Distribution of O_3, SO_2, and NO_2

Very little information can be obtained on the vertical distribution of the trace gases.

Measurements at different wavelengths (technique of combining UV, visible, and IR measurements) provide some vertical information:
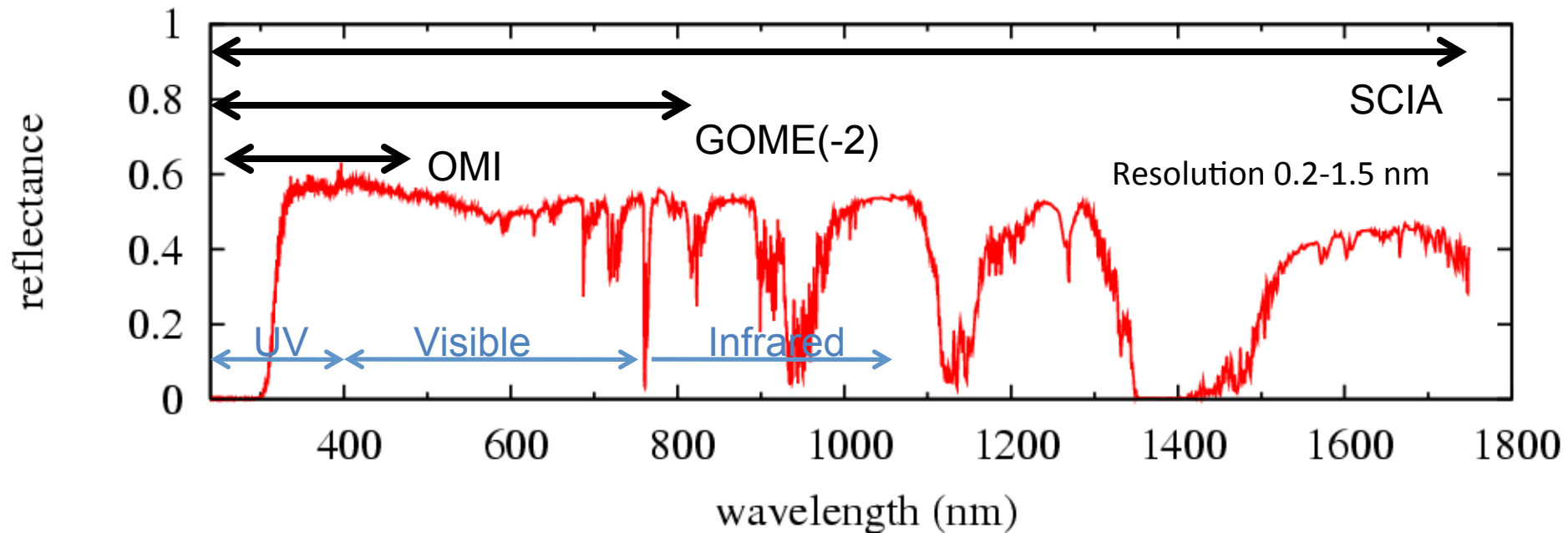
- The penetration depth of photons increases with increasing wavelengths
- Example: volcanic plumes of SO2
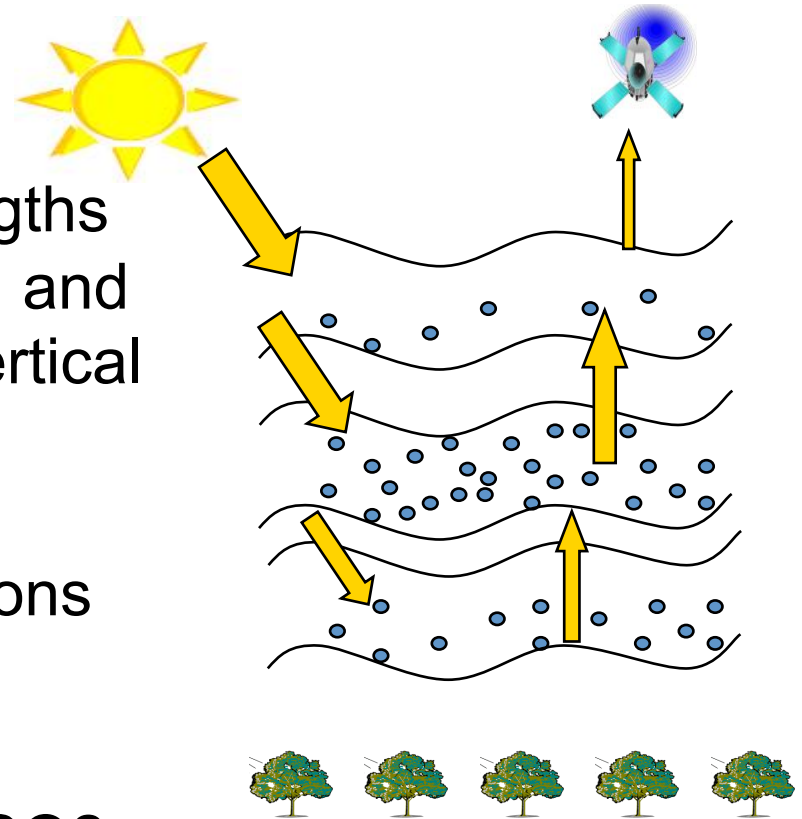
Hyper-spectral Instruments

Satellite UV-visible spectrometers

• GOME	ERS-2	240 – 800 nm
• SCIAMACHY	Envisat	240 – 1750 nm
• OMI	EOS-Aura	270 - 500 nm
• GOME-2	Metop-A	240 – 800 nm

Data Formats and Resolutions

| Data Level	Description
Level 0	Raw data at full instrument resolution.
Level 1A	Raw data including radiometric and geometric calibration coefficients and geo-referencing parameters (e.g., platform ephemeris) computed and appended but not applied to Level 0 data.
Level 1B	Level 1A data that have been processed to sensor units (not all instruments have Level 1B source data).
Level 2	**Derived geophysical variables at the same resolution and location as Level 1 source data.**
Level 2G and 3	**Variables mapped on uniform space-time grid scales, usually with some completeness and consistency.**
Level 4	Model output or results from analyses of lower-level data (e.g., variables derived from multiple measurements).

Spatial Resolution: Trace Gases

- The spatial resolution of current satellite instruments (10's of km diameter) is good enough to map tropospheric concentration fields at local to regional scales and fine enough to resolve individual power plants and large cities.

- For those species having short atmospheric life times (e.g. NO_2), the averaging over larger satellite pixels can lead to significant dilution of signals from point sources, complicating quantitative analysis and separation of emission sources.

- For quantitative analysis – Level 2 and high-resolution gridded Level 3 data are optimal.

> Advantages of using Level 3 vs Level 2 data are:
> - Uniform grid
> - One file per day
> - Smaller sized files
> - Quality flags and filtering criteria have been applied

Perspective …
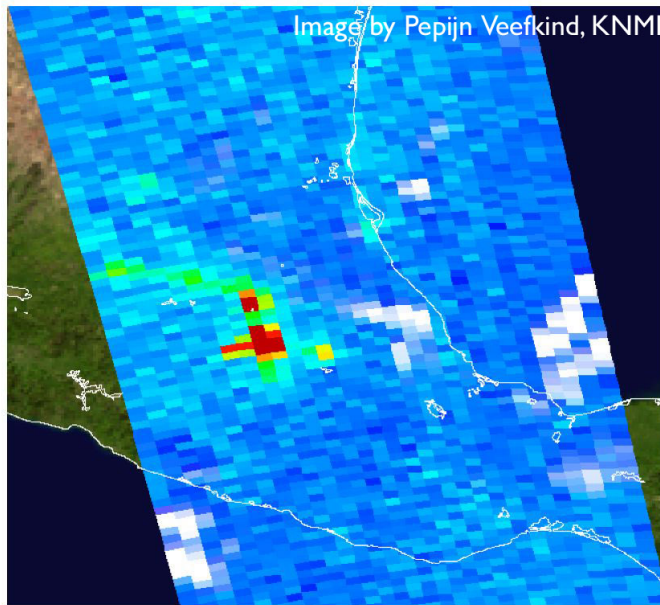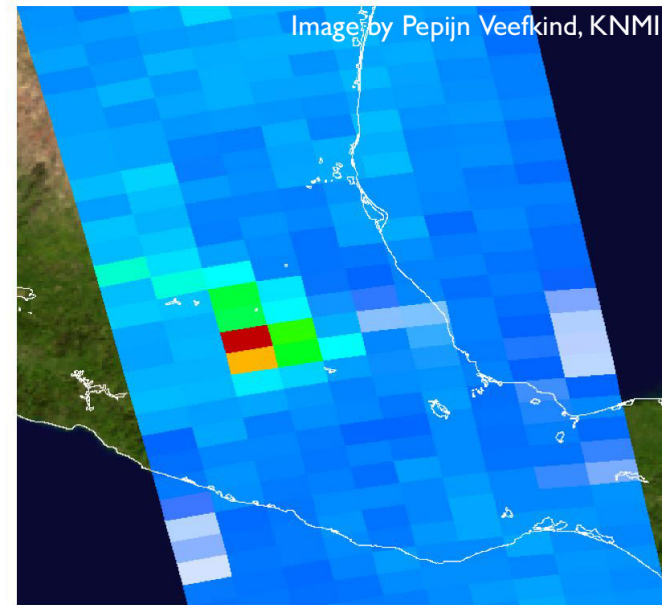
OMI 24x13 km^2 Approx. GOME-2 72x39 km^2

**Mexico City, Jan. 20, 2005**

Quantification of gas abundances

Satellite Tracer	Units
OMI O_3, SO_2	Dobson Units
OMI NO_2 Column Amounts (also AIRS and MOPITT CO)	Molecules/cm^2
AIRS and MOPITT CO Vertical Levels	Volume mixing ratio
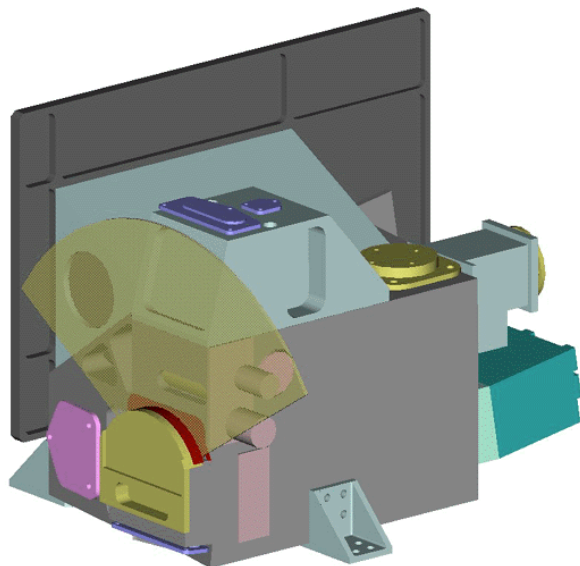
- Launched on July 15, 2004 on the NASA EOS Aura Satellite

- Nadir-viewing UV/Visible
  - 270-310 nm @ 0.6 nm
  - 310-500 nm @ 0.45 nm

- 1:40 PM equatorial crossing time

- 13x24 km^2 at nadir

- Daily global coverage.
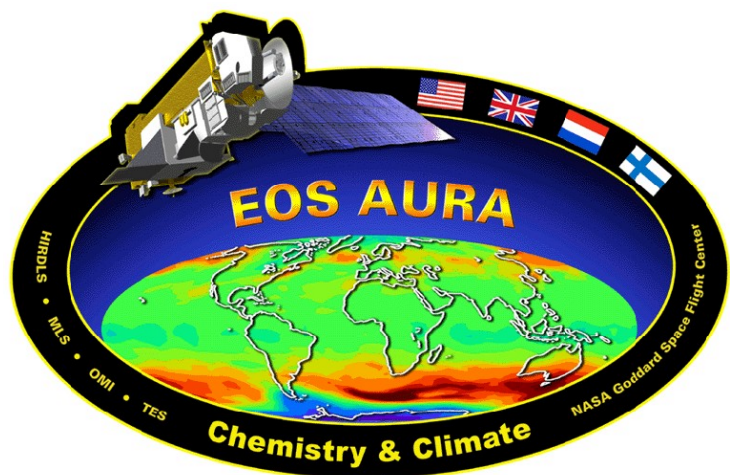
Products:
Total Column O_3
Tropospheric Column O_3 (experimental
But not applicable in the mid-latitudes)
Aerosol optical depth (in UV)
Column Formaldehyde
Column NO_2
Column SO_2

EOS AURA
Chemistry & Climate

Data Granule

The product file, called a **data granule**, covers the sunlit portion of the orbit with an approximately 2600 km wide swath containing 60 binned pixels or scenes per viewing line.

During normal operations, 14 or 15 granules are produced daily, providing fully contiguous coverage of the globe.
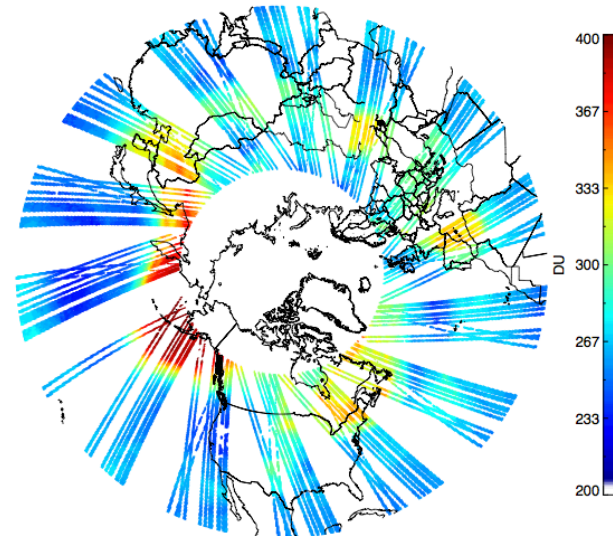

OMI-Aura_L2-OMNO2_2008m0720t2016-o21357_v003-2008m0721t101450.he5
Effective cloud fraction
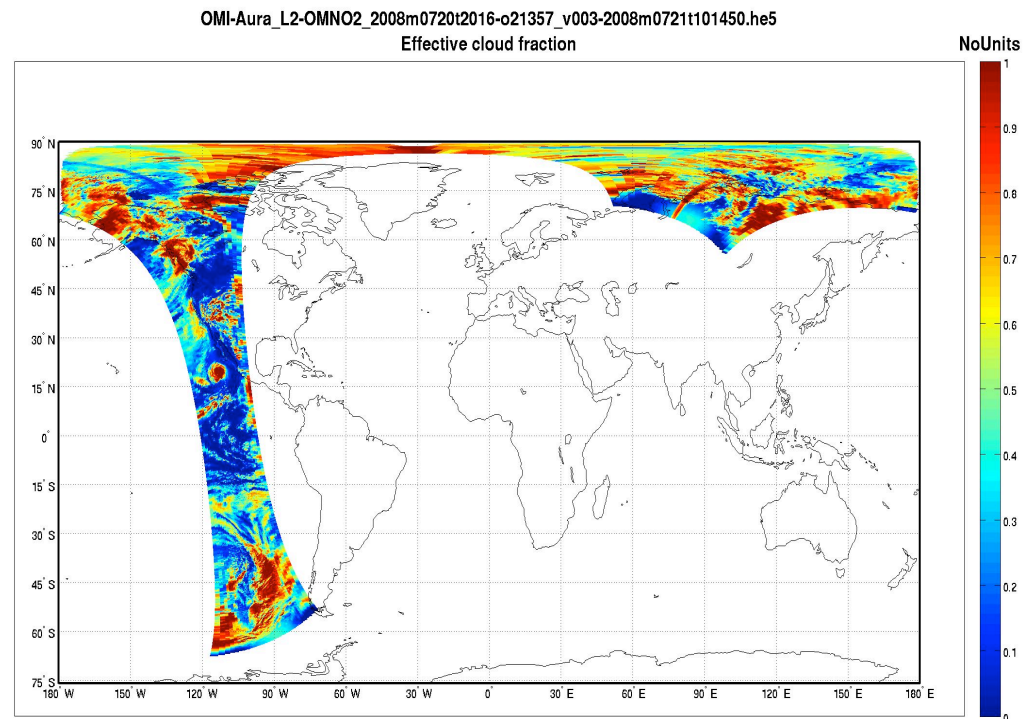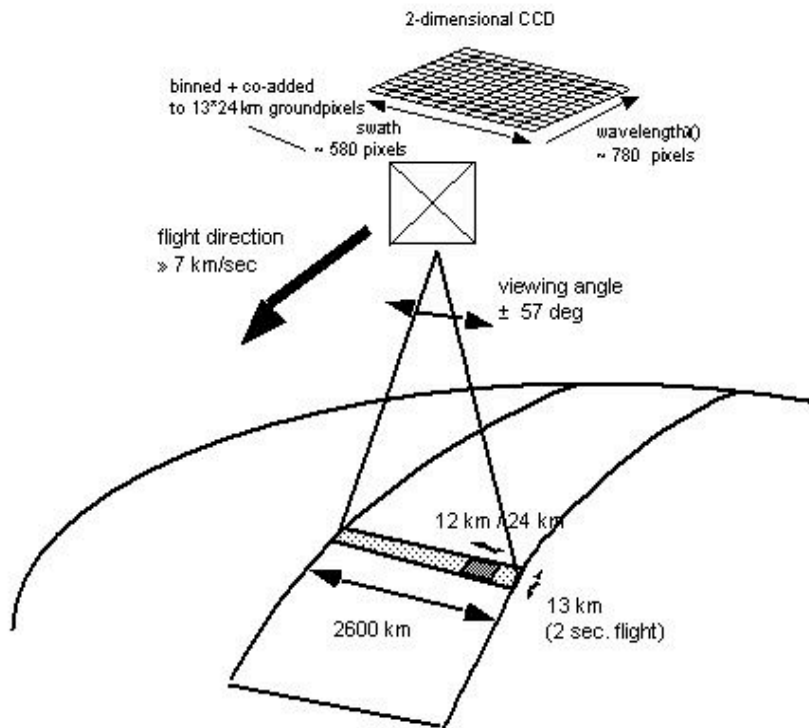
Important information regarding OMI

Almost 50% data loss since 2008
(row anomaly effect)

Affects O_3, SO_2, and to some extent NO_2 OMI Products

OMI TO3 L2G: 2006 11 3
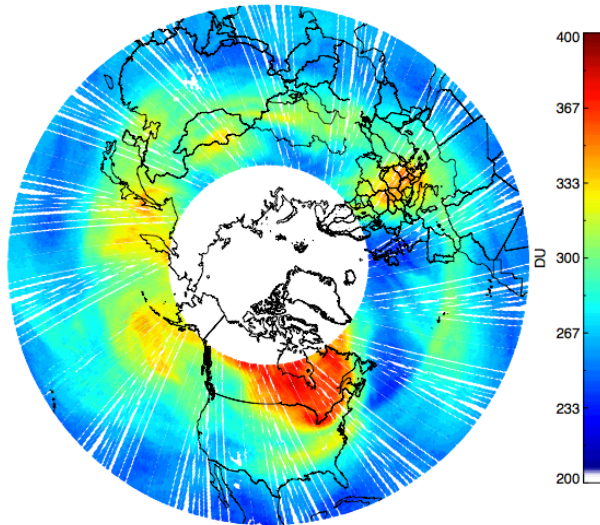
OMI TO3 L2G: 2010 11 1

OMI Ozone and Formaldehyde

OMI Ozone in the Troposphere

OMI is NOT sensitive to ozone near the surface.
There are tropospheric ozone products in development but they currently cannot be used for AQ monitoring.

Retrieval of boundary layer O_3 from satellite remote sensing remains a daunting task.

OMI Formaldehyde (CH$_2$O)

Data is reliable for the 2004-2009 time period only. Data re-processing is planned to account for the growing background noise and row anomalies.

HCHO is a proxy for isoprene emissions.

Source: Randall Martin, Satellite remote sensing of surface air quality, Atmos. Environ. 42(34), 7823-4843, 2008.
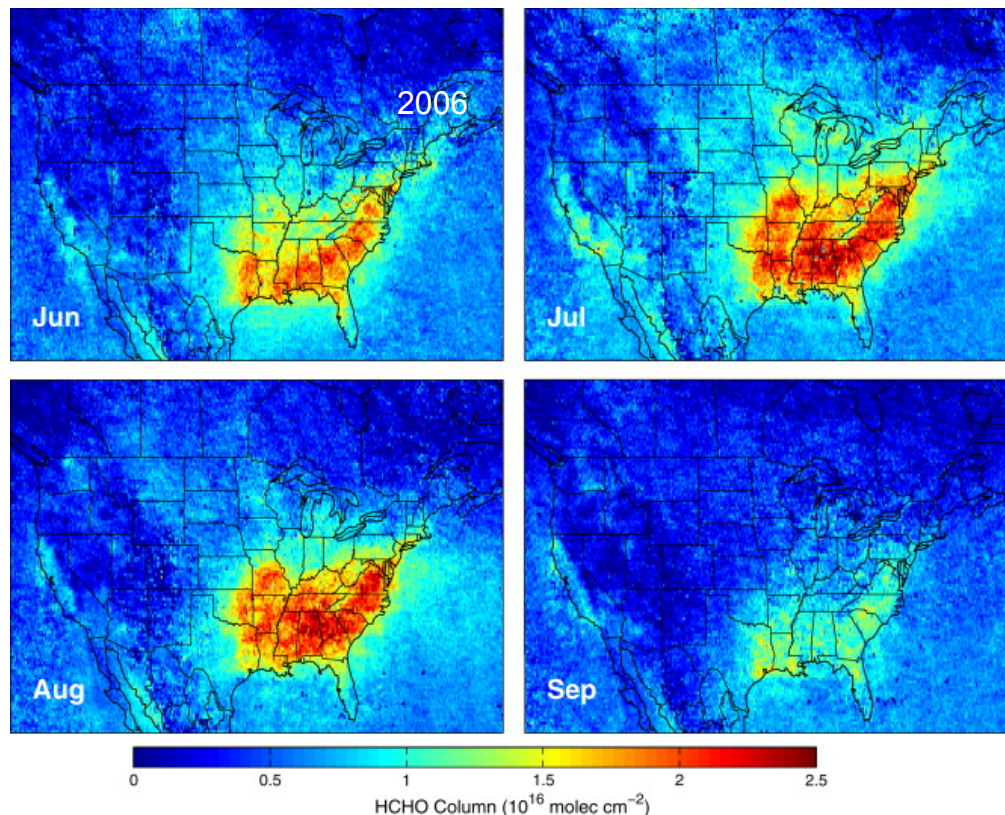
- Planetary Boundary Layer (PBL) and Volcanic SO_2

- Tropospheric Column NO_2

OMI SO$_2$ in the boundary Layer

Data Set Short Name = OMSO2e

> Product Level = 3
>
> Begin Date = October 1, 2004
>
> Resolution = 0.25°lon x 0.25°lat
>
> Version = 003

Cloud-screened best measurement

> Production Frequency: Daily
>
> Granule (File) Coverage: 15 orbits
> File Size(Approx): 5 MB

Contains **best** pixel data, screened for OMI row anomaly, clouds, and other data quality flags.
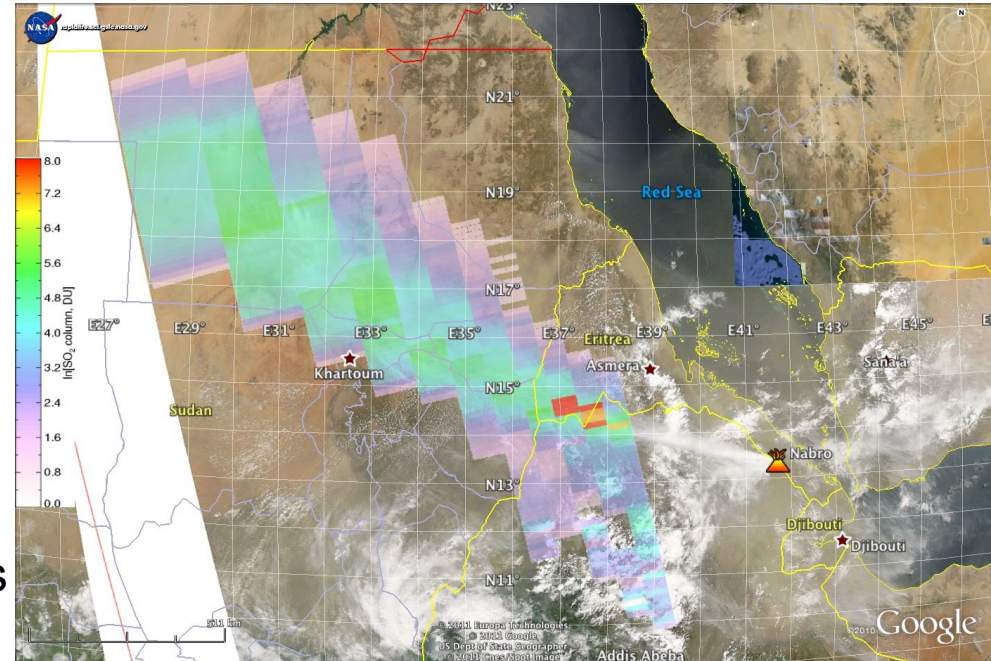
Aqua MODIS visible image of the Nabro (Eritrea) eruption on June 13, 2011 and the SO2 plume overlaid.

Data here: http://disc.sci.gsfc.nasa.gov/Aura/data-holdings/OMI/omso2e_v003.shtml
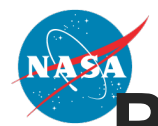
Perspective: What is considered high SO_2?

2005-2010 mean over the Canadian oil sands
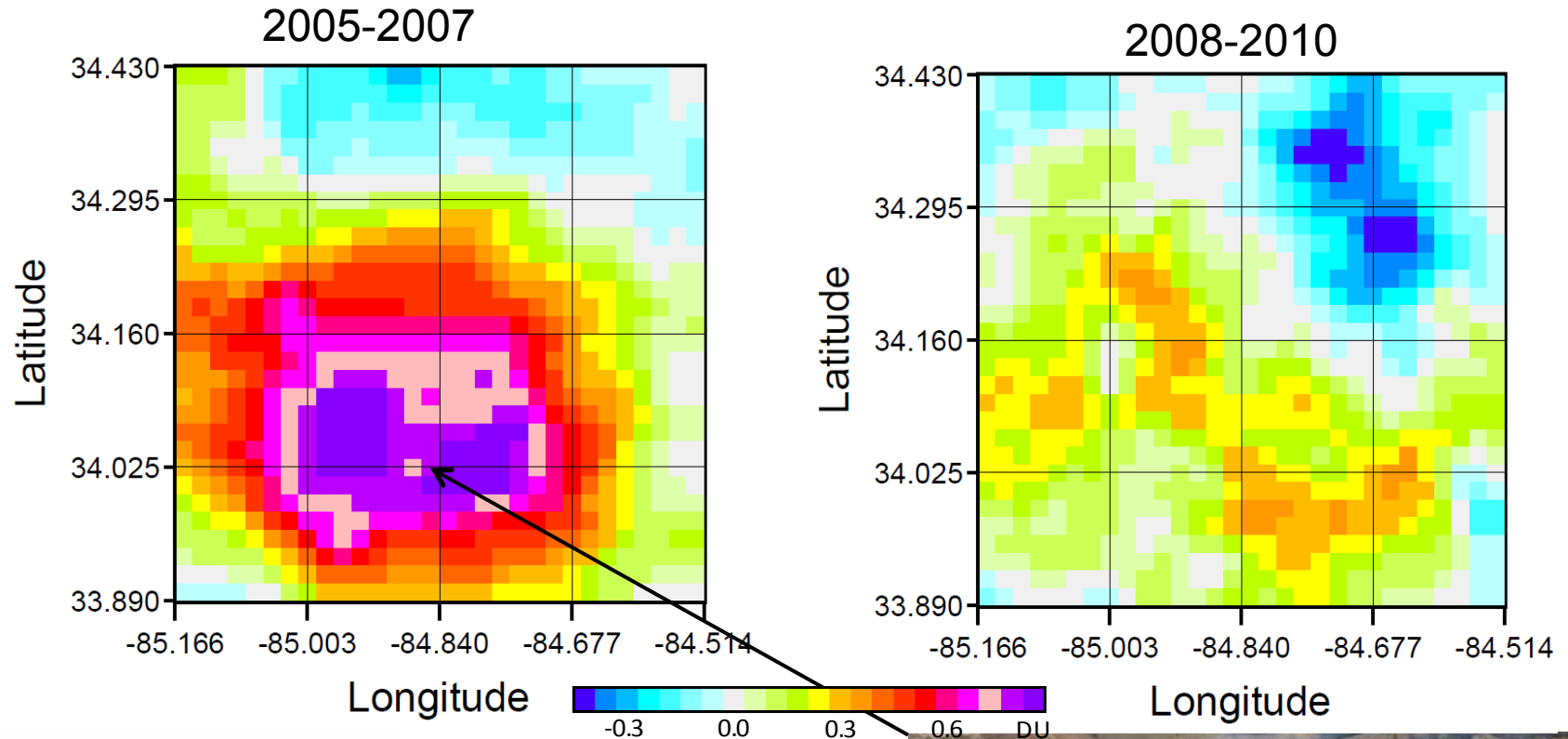

• Fort McMurray

0.1   0.2   0.3   0.4
DU
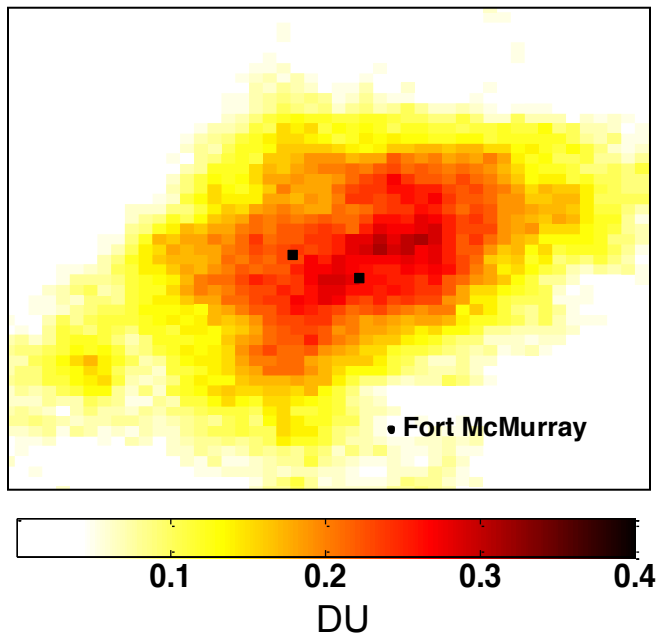
McLinden, C. A., et al. (2012), Air quality over the Canadian oil sands: A first assessment using satellite observations, Geophys. Res. Lett., 39, L04804, doi:10.1029/2011GL050273.

OMI SO_2 from the Kasatochi Volcano eruption in the Alaskan Aleutian Islands on 2008 August 8 continued to spread eastward on August 12.

In [sulfur dioxide, Dobson Units]

0   2.5   5

SO_2 absorption spectrum

305 - 330nm

λ
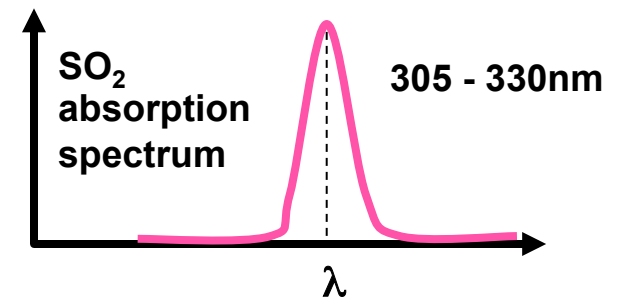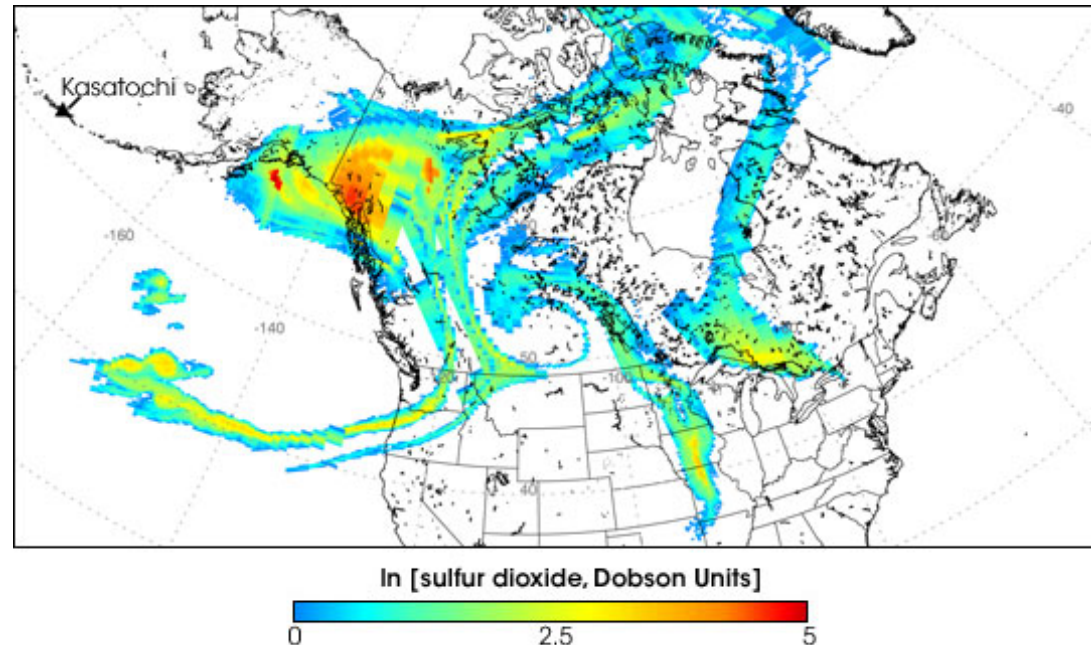
US Source #1.Bowen Coal Power Plant, Georgia (3500 MW), SO$_2$ emissions: 170 kT in 2006

2005-2007

2008-2010

Sulfur Dioxide Emissions Total
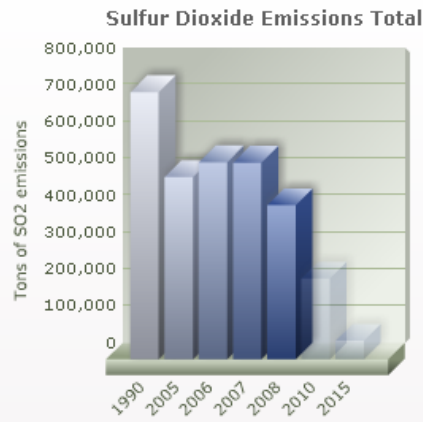
"In **2008**, the mammoth construction program yielded the first scrubbers, sophisticated equipment that will reduce our overall systems emissions by as much as 90 percent"
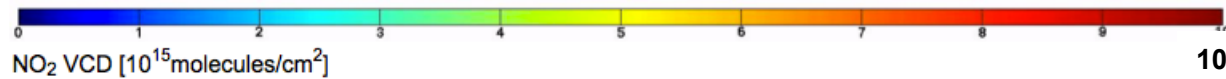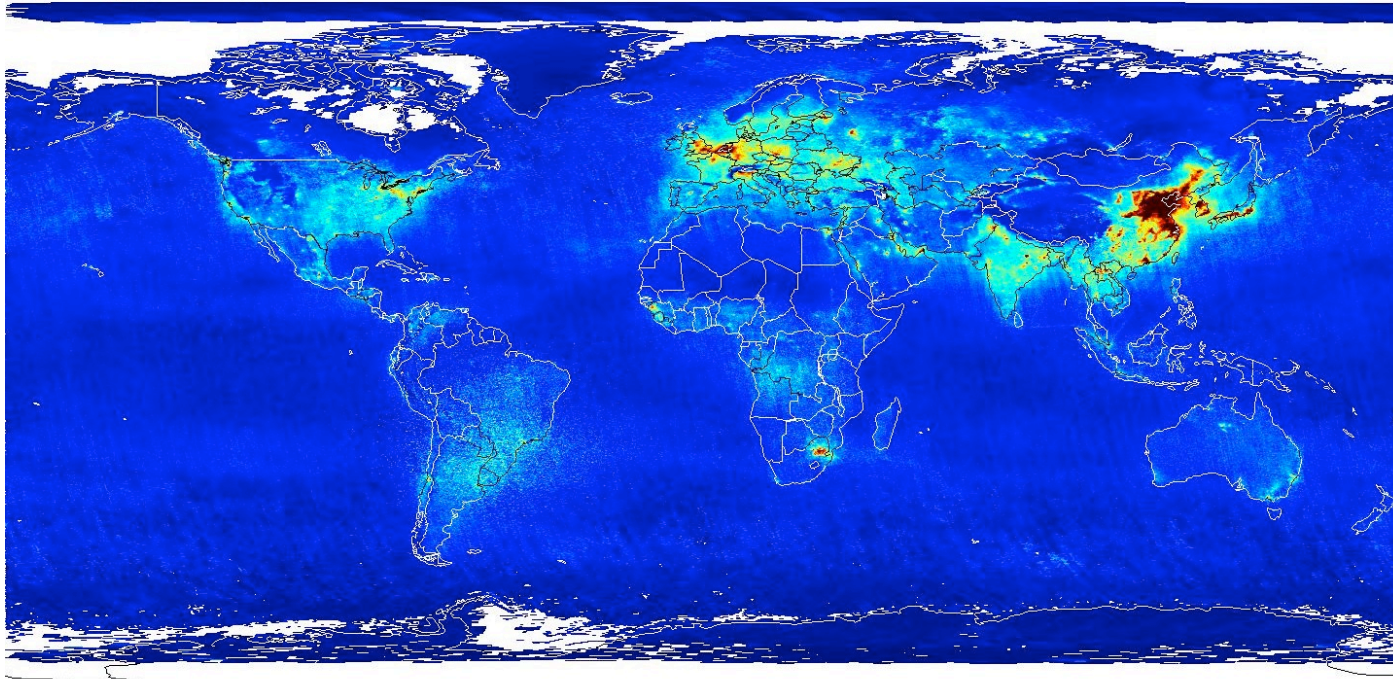**Georgia Power website**

V. Fioletov, et al., 2011

OMI NO$_2$

March 2011

NO$_2$ VCD [10^{15}molecules/cm^2]

10

NO$_2$ absorption spectrum

420-450nm

λ
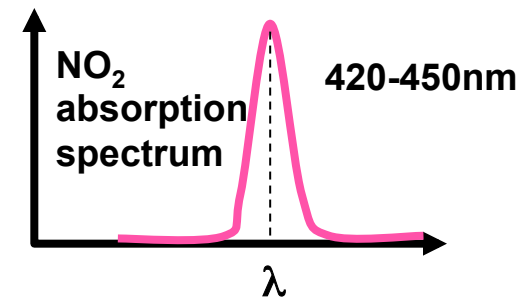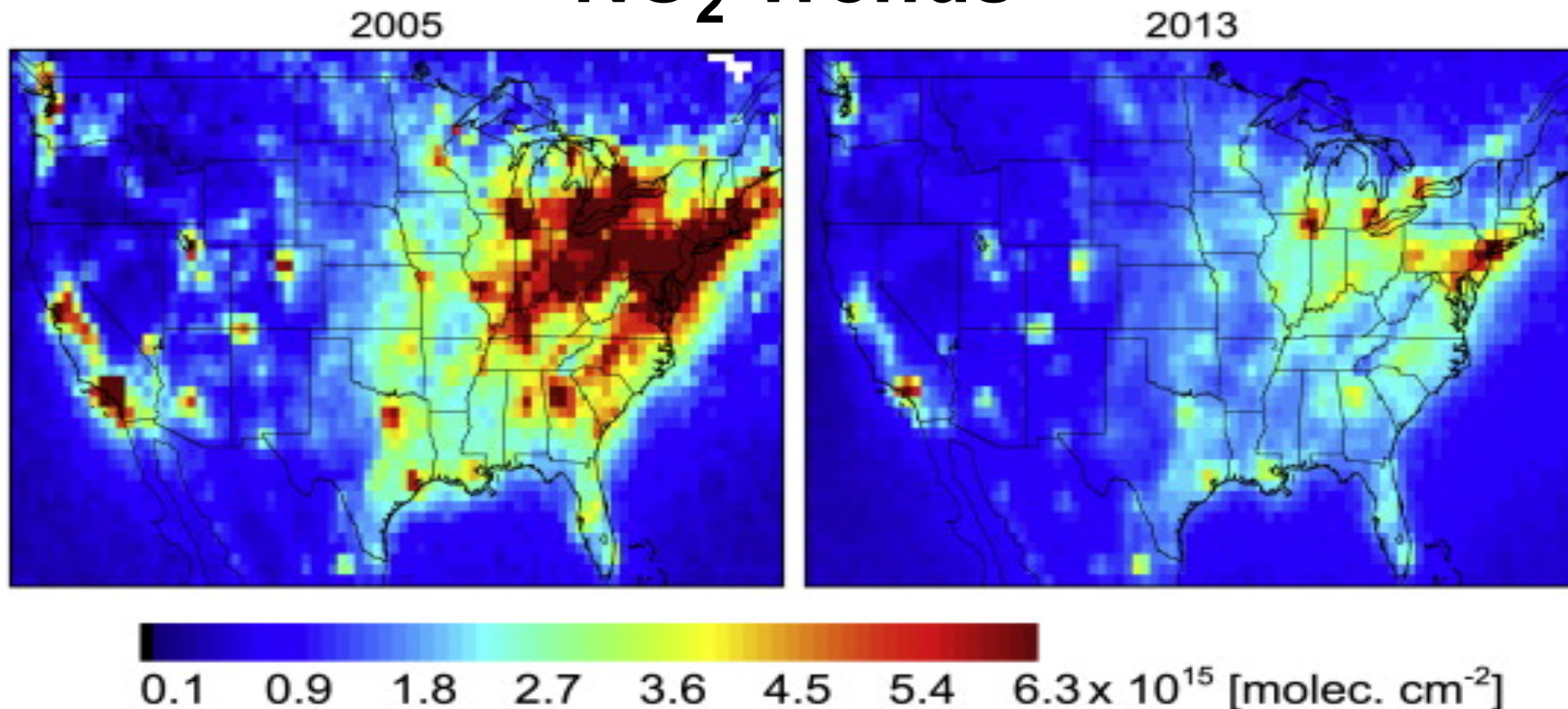
NO$_2$ Trends

Fig. 1. Annual average OMI tropospheric NO2 VCDs at 1/2° latitude × 2/3° longitude spatial resolution for 2005 (left) and 2013 (right).

Lok N. Lamsal, Bryan N. Duncan, Yasuko Yoshida, Nickolay A. Krotkov, Kenneth E. Pickering, David G. Streets, Zifeng Lu

Satellite and AQS NO$_2$ Trends
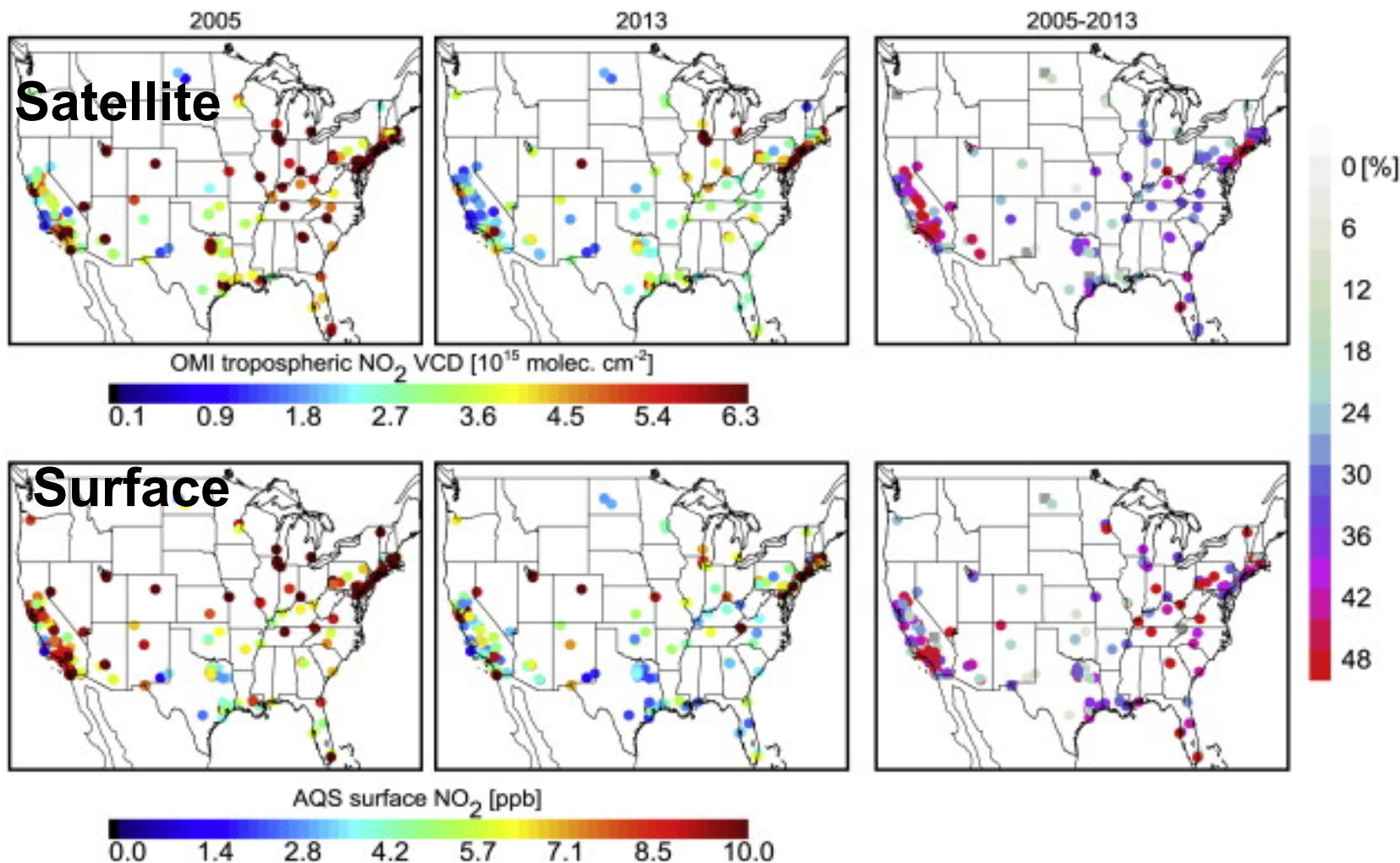
Lok N. Lamsal, Bryan N. Duncan, Yasuko Yoshida, Nickolay A. Krotkov, Kenneth E. Pickering, David G. Streets, Zifeng Lu

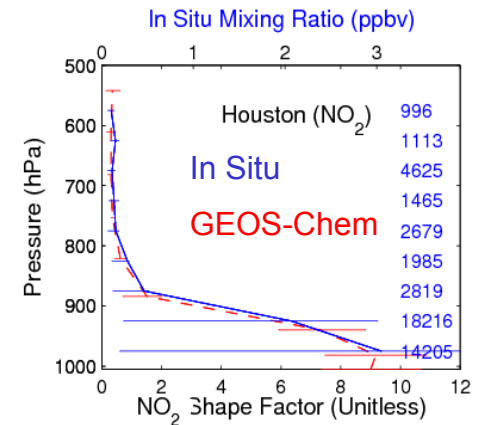# Estimating Satellite based Surface NO$_2$

NO2 Column
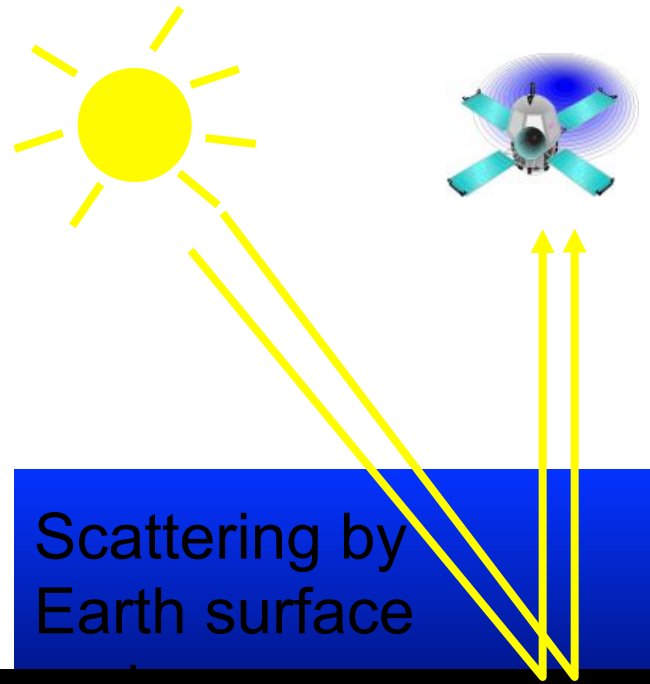
Model Profile

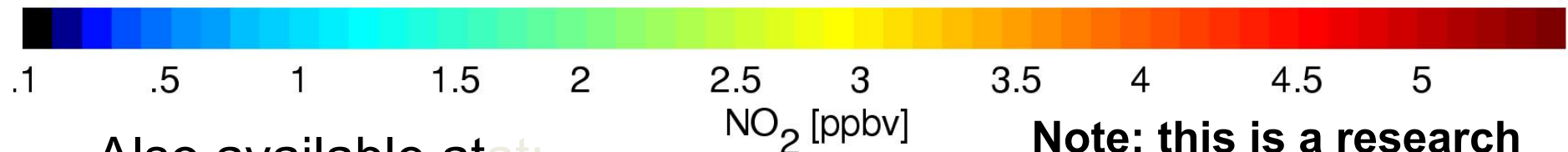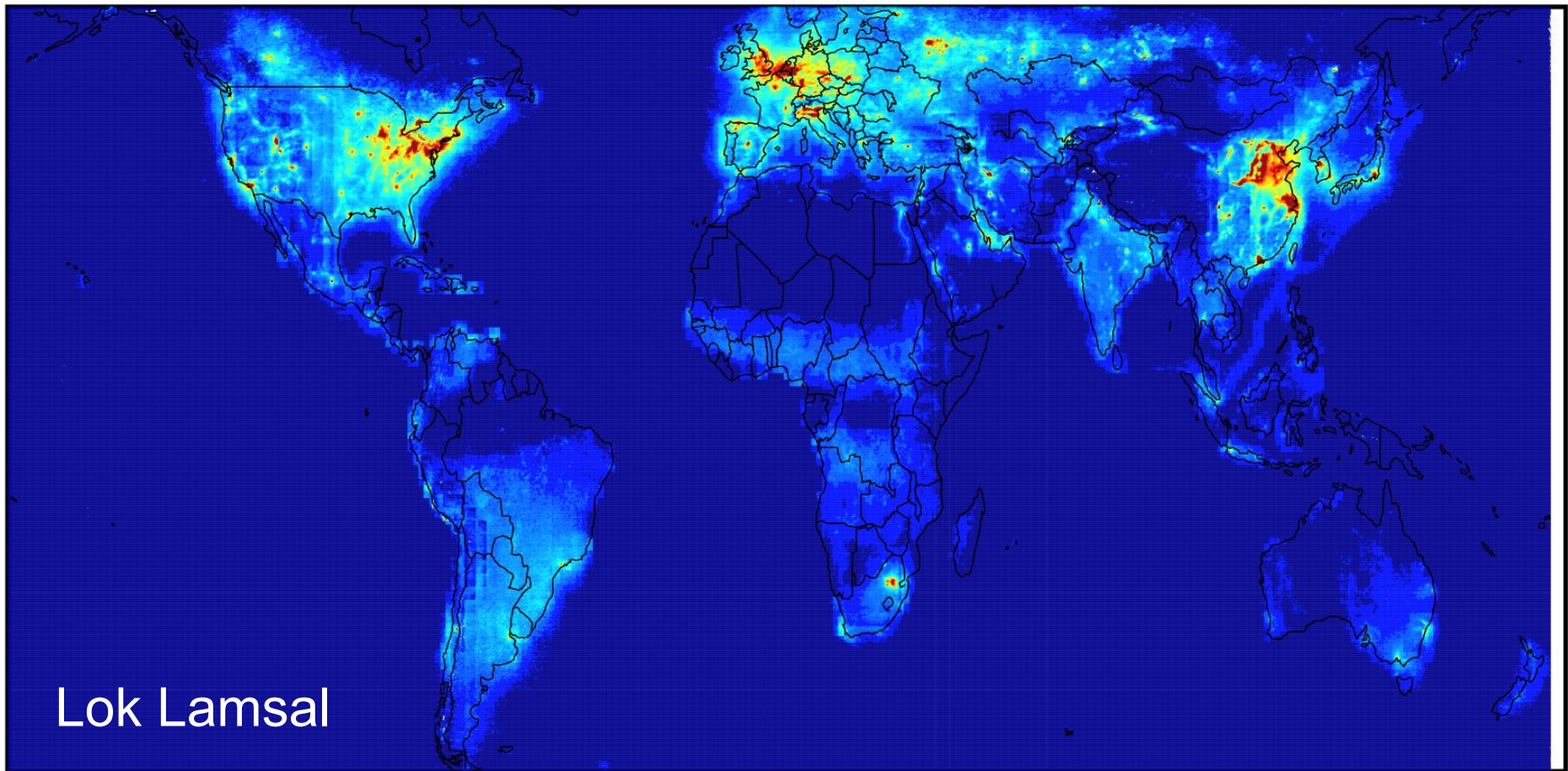Scattering by Earth surface and atmosphere
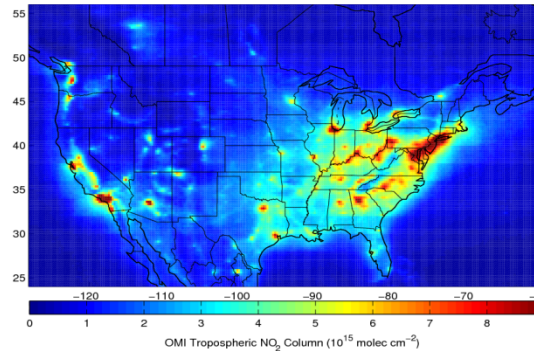
$$S_O = \Omega_O \left[\frac{S_M}{\Omega_M} \right]$$

S → Surface Concentration

Ω → Tropospheric column

Courtesy of Randall Martin

Ground-Level Afternoon NO$_2$ Inferred From OMI for 2005

Lok Lamsal

NO$_2$ [ppbv]

Also available at at:
http://fizz.phys.dal.ca/~atmos/

Note: this is a research product and not an official NASA product
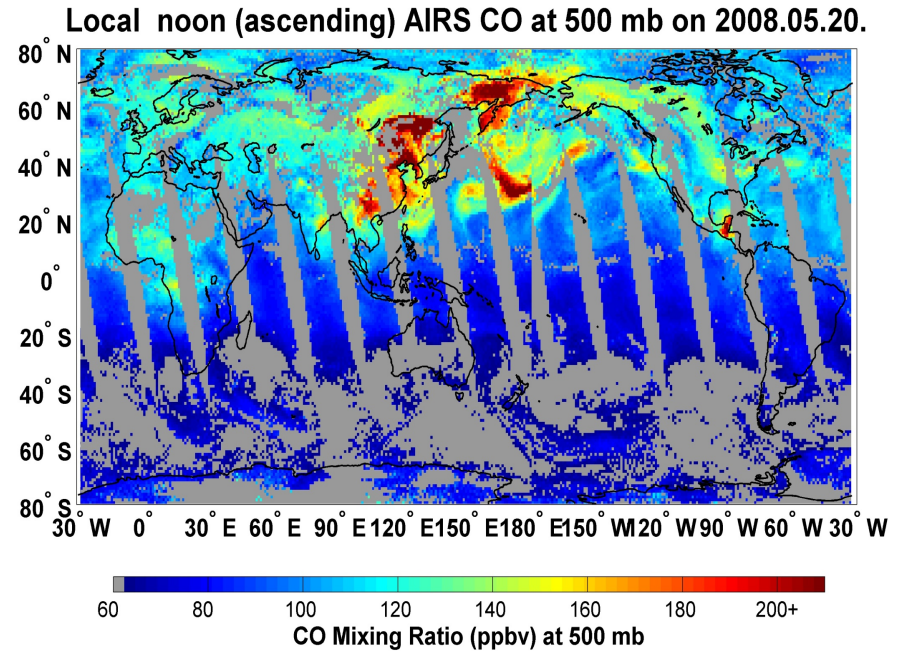
Carbon Monoxide

Total Column Density

Also Sensitive to the vertical distribution of CO
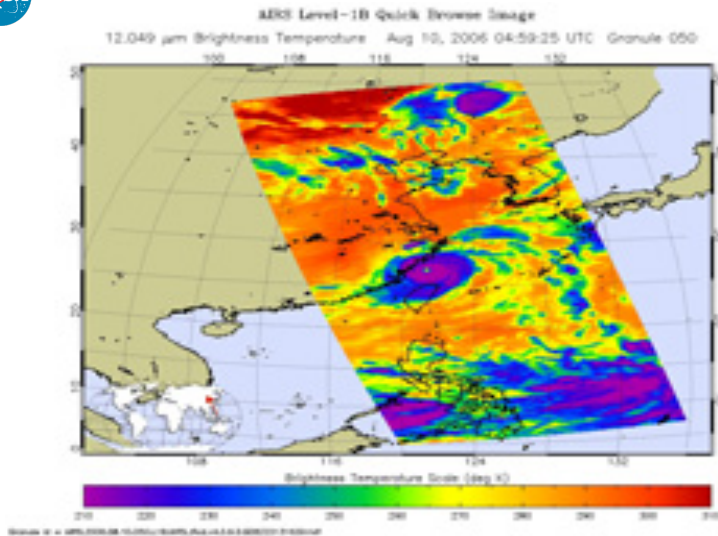
Greatest sensitivity to CO variability is at 500 mb
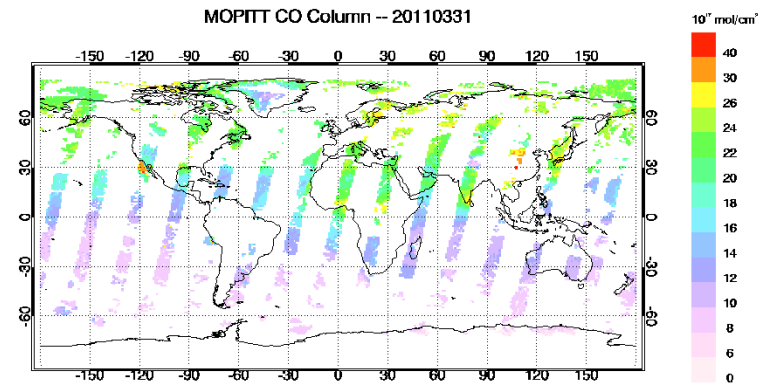
↓

Mixing ratio can be larger away from source

Local noon (ascending) AIRS CO at 500 mb on 2008.05.20.

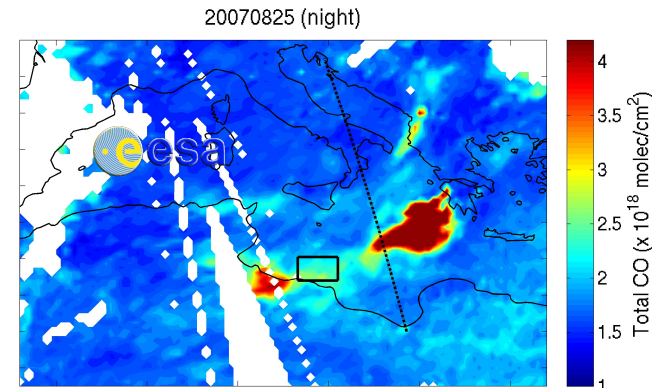CO Mixing Ratio (ppbv) at 500 mb

Current CO Sensors

AIRS – Atmospheric Infrared Sounder

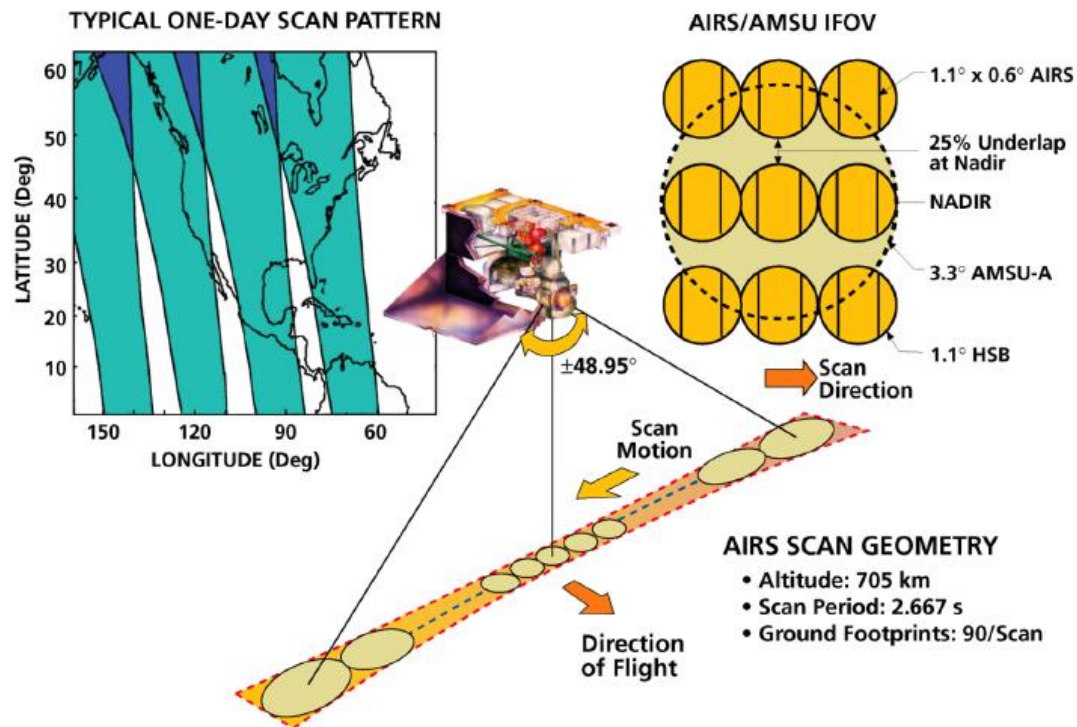**MOPITT – Measurements of Pollution in The Troposphere**

IASI – Infrared Atmospheric Sounding Interferometer

AIRS

- Operational since Sept. 2002

- A nadir sounding instrument.

- Pixel size = 14 km at nadir

    41 x 21 km edges

- Swath width = 1650 km

- Equator Crossing times

  - 13:30 AM (Ascending orbit)

  - 13:30 PM (Descending orbit)

- Column measurements

  - Units = molecules/cm^2

- Profile measurements

  - 9 vertical layers (904.866 hPa – 0.016 hPa)

  - Profile Units = Volume mixing ratio

- Total Column CO measurements provided in units = molecules/cm2

- Data Source: Level 2 pixel and Level 3 gridded 1°×1° resolution

- Current Version 6

HOMEPAGE: http://airs.jpl.nasa.gov

TYPICAL ONE-DAY SCAN PATTERN

AIRS/AMSU IFOV

1.1° x 0.6° AIRS
25% Underlap at Nadir
NADIR
3.3° AMSU-A
1.1° HSB
Scan Direction
±48.95°
Scan Motion
Direction of Flight

AIRS SCAN GEOMETRY
- Altitude: 705 km
- Scan Period: 2.667 s
- Ground Footprints: 90/Scan

Satellite measurements of Carbon Monoxide (CO) is an excellent tracer of Biomass burning, i.e. forest fires

• Unlike MOPITT, AIRS has excellent global coverage with 'minor' gaps particularly over CONUS!

• One can easily track biomass burning plumes.

○ AIRS swath width is ~ 1650km whereas MOPITT 640km.

○Twice daily coverage with AIRS (daytime and nighttime).
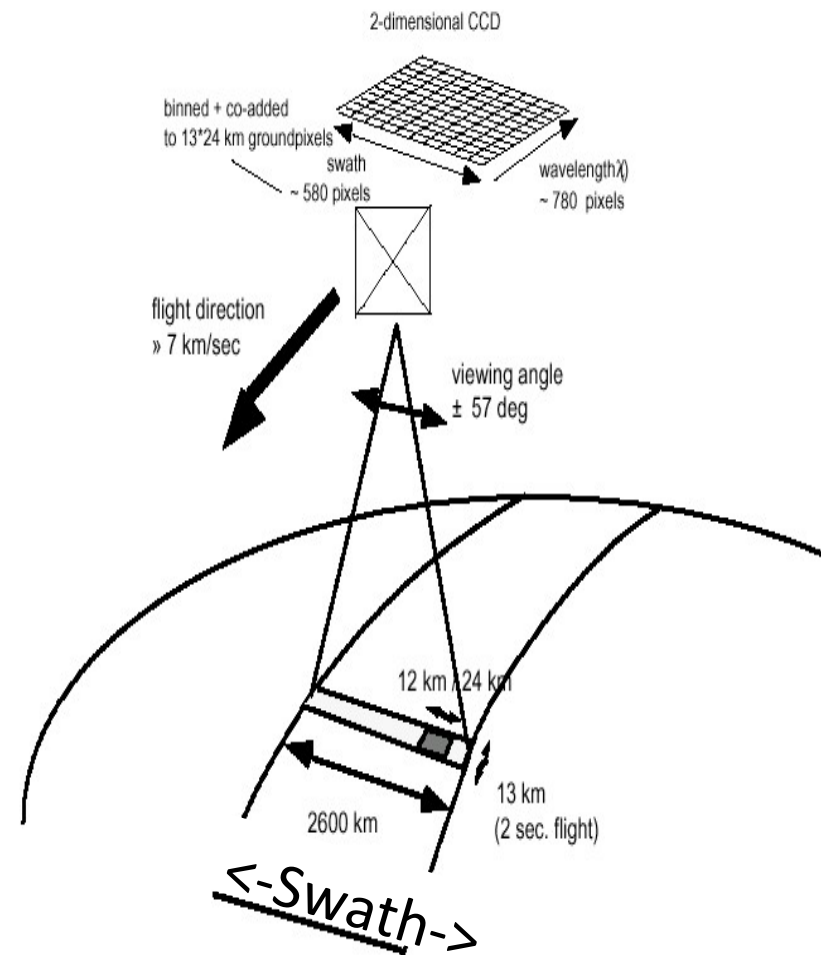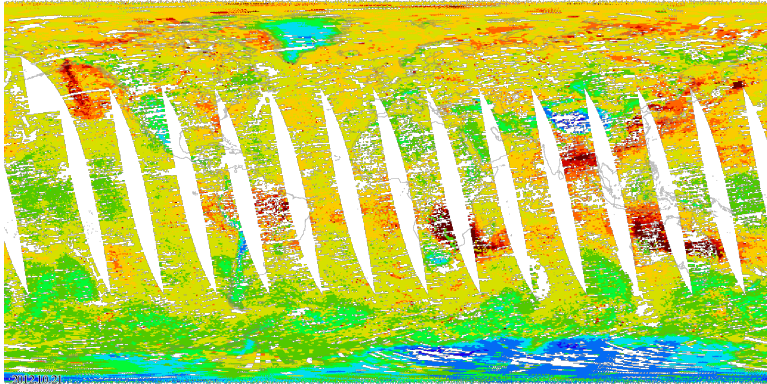
Ascending Orbit = Daytime
Descending Orbit = Nighttime

2-dimensional CCD

binned + co-added
to 13*24 km groundpixels

swath
~ 580 pixels

wavelength(λ)
~ 780 pixels

flight direction
» 7 km/sec

viewing angle
± 57 deg

12 km / 24 km

13 km
(2 sec. flight)

2600 km

<-Swath->

Figure 2.1   Measurement principle of OMI.

AIRS vs MOPITT CO

AIRS Level 2
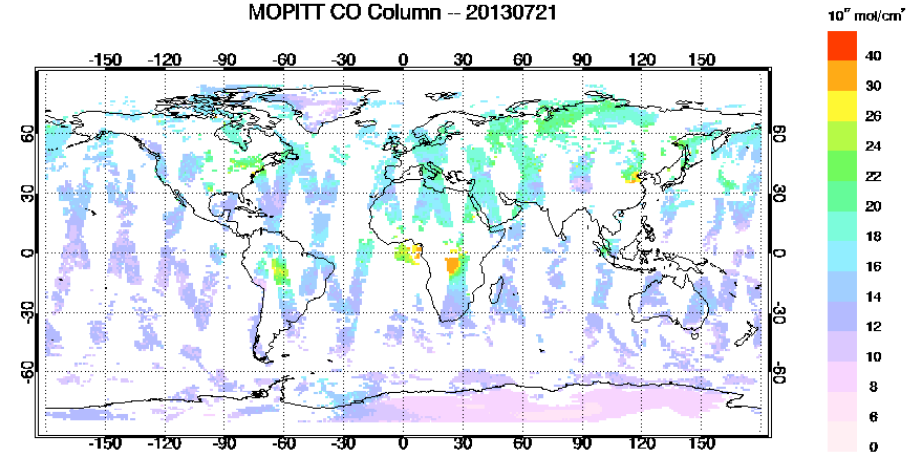From NRT
Website

AIRS Level 3 1x1deg
from GIOVANNI

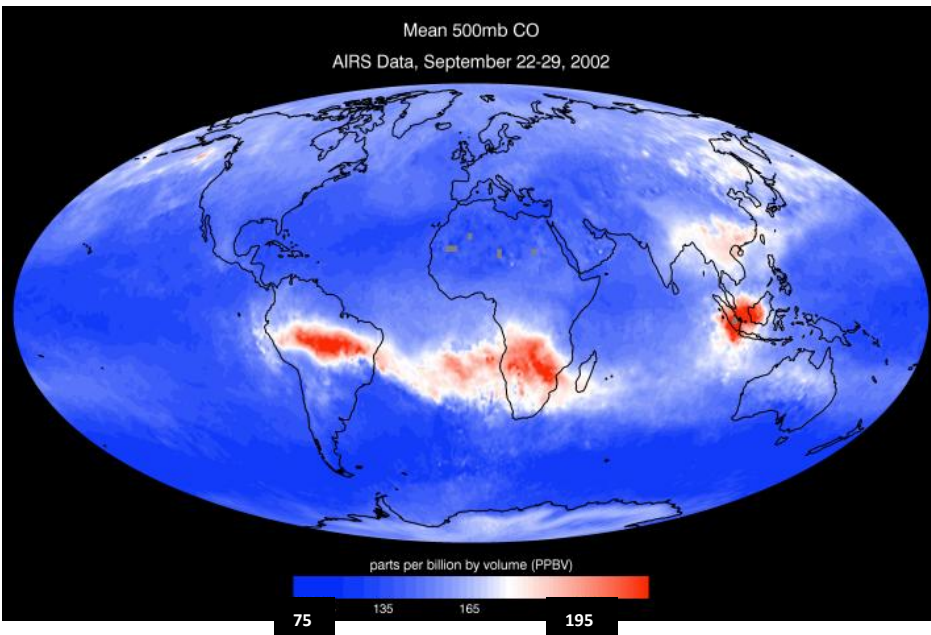AIRX3STD.005 total column CO_ascending (CO_total_column_A) [10E18 molecules/cm2]
(20Oct2007)

0.695   1.547   2.398   3.25   4.102   4.954
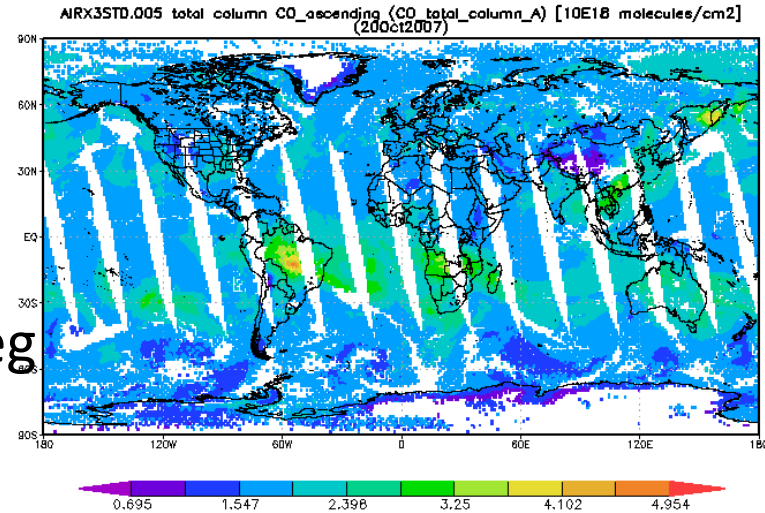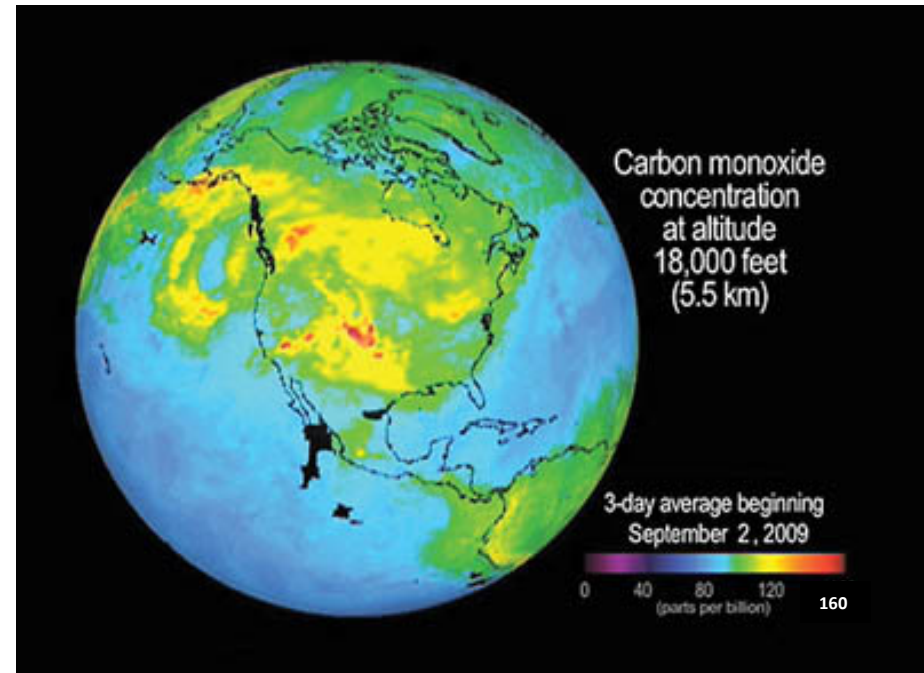
MOPITT CO Column -- 20130721

10¹⁷ mol/cm²

MOPITT
Level 3
1x1deg

Long Range Transport of CO

DATA PRODUCT SUMMARIES

OMI SO2 Gridded Product Summary

SO$_2$ Product	Level	Data Short Name	Sensitivity	Use
PBL SO$_2$	L3, 0.25^{o}x0.25^o	OMSO2e	0.6 km	Fossil fuel, industry
TRL SO$_2$	L2G, 0.25^{o}x0.25^o	OMSO2G	3 km	Industry outflow
TRM SO$_2$	L2G, 0.25^{o}x0.25^o	OMSO2G	5 km	optimized for volcanic degassing with vents at ~5km altitude or above and emissions from effusive eruptions.
STL SO$_2$	L2G, 0.25^{o}x0.25^o	OMSO2G	15 km	intended for use with explosive volcanic eruptions

Caveat: Unlike the OMSO2e 'best' product. L2G data are NOT screened for clouds, sza, quality flags, row anomalies.

Level 2 pixel (footprint) size at nadir and comparison chart

- **AIRS** — 14 x 14 km
- **MOPITT** — 22 x 22 km
- TES — 8.3 km / 5.3 km
- SCIAMACHY — 30 km / 60 km
- **IASI** — 12 x 12 km

	MOPITT	AIRS	TES	IASI	SCIAMACHY
Product/pixel size	22 x 22 Km	14 x 14 km	5.3 x 8.3 KM 100 M between pixels	50 KM 12 x 12 KM	30 x 60KM
Swath width	650 KM	1650 KM	N/A	2200 KM	1000 KM
Global Coverage/ Repeat Cycle	3 Days Composite for global coverage	2X per day (day and night)	16 days Repeat Cycle	2X per day (day and night)	6 Days
Overpass time	10:30 AM	13:30	2:30 AM / PM	9:30 AM/PM	10:00 AM
Product Resolution	L3 1 Degree grid	L3 1 Degree grid	L3 5x8km	NO L3 Product	L3 0.5 Degree grid
Products available	L2 L3 Daily, Monthly	Level 2 (granule) Level 3	L2 granule	L2 NOAA and ESA	2B – swath 3 – global
Vertical sensitivity	Mid and lower troposphere	Mid-Troposphere	mid and lower troposphere	mid troposphere	Total column only
Product accuracy	TIR – 10% Near Surface 30%	10 – 20%	20%	< 10%	10 – 20%
Other notes	TIR and NIR Channels	QA flags in L2 and L3	Report data for clouds 0 -25% Simultaneous trace gas	250 KM sampling ESA Should avg. to 4x5 deg.	